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FORMABILITY OF WARM DEEP DRAWING PROCESS FOR AA1050-H18 RECTANGULAR CUPS

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ABSTRACT

In this present work, a statistical approach based on Taguchi Techniques and finite element analysis were adopted to determine the formability of rectangular cup using warm deep drawing process. The process parameters were thickness of blank, temperature, coefficient of friction and strain rate. The experimental results were validated using a finite element software namely D-FORM. The AA1050 –H18 sheets were used for the deep drawing of the rectangular cups. The blank thickness by itself had a significant effect on the effective stress and the height of the rectangular cup drawn. The reduction of the drawing force was perceived with the increase of temperature. The increase in the effective stress was found due to the requirement of high drawing pressures for thick sheets to undergo plastic deformation. The formability of the rectangular cups was outstanding for the surface expansion ratio greater than 3.0. The damage was less in the rectangular cups drawn with the friction coefficient of 0.075. The formability of deep drawn rectangular cups is difficult with blank thickness less than 1mm.

KEYWORDS: AA1050-H18, Warm Deep Drawing, Thickness, Temperature, Coefficient Of Friction, Strain Rate, Finite Element Analysis, Formability

INTRODUCTION

Wrinkling and tearing rupture are the common failures of drawn cups during the deep drawing process. The process variables, which affect the failure of the cup drawing process, include material properties, die design, and process parameters such as temperature, coefficient of friction, strain rate, blank holding force, punch and die corner radii and drawing ratio. The ductility of common aluminum alloys increases with temperature. Thus, the forming at elevated temperatures close to the recrystallization temperature of about 300 °C, also called warm forming, is one of the promising methods to improve formability. Takuda et al. (2002) simulated the deformation behavior and the temperature change in deep drawing of an aluminum alloy sheet and successfully predicted the forming limit and necking site by comparing the numerical results with experimental results. Rao et al. (1996) made a research on low carbon steel. The results conclude that with enhancement of strain rate and reduction of temperature, the tensile strength increases and entire flow curve of material increases its level. Friction is another important factor that influences the deep drawing process. In metal forming processes, the friction influences the strain distribution at tool blank interface and drawability of metal sheet. Yang (2010) has simulated the deep drawing process to analyze friction coefficient and strain distribution by combining an elastic-plastic FEM code with a friction model. In the experimental work carried out by Reddy et al. (2012) on the warm deep drawing process of the EDD steel it has been observed that the extent of thinning at punch corner radius is found to be lesser in the warm deep-cup drawing process of extra-deep drawing (EDD) steel at 200^0C. In another work performed by the author (2012) on the cup drawing process using an implicit finite element analysis, the thinning is observed on the

vertical walls of the cup with high values of strain at the thinner sections. In the finite element simulations, a forming limit diagram (FLD) has been successfully applied to analyze the fracture phenomena, as referred to Shehata et al (1978). Here, the fracture behavior is analyzed by comparing the strain status corresponding to elements.

AA1050 is known for its excellent corrosion resistance, high ductility and highly reflective finish. Applications of AA1050 are typically used for chemical process plant equipment, food industry containers, architectural flashings, lamp reflectors, and cable sheathing. AA1050 aluminum alloy is not heat treatable. It is difficult to deep draw and to have minimum wall thickness of less than 1 mm. Therefore, it is expensive to exploit the combination of high strength and thin wall cups using deep drawing process.

In the present work, the formability of warm deep drawing process was assessed during the fabrication of AA1050-H18 rectangular cups. The design of experiments was carried out using Taguchi technique and the warm deep drawing process was executed using the finite element analysis software namely D-FORM 3D. The investigation was focused on the process parameters such as blank thickness, temperature, coefficient of friction and strain rate.

MATERIALS AND METHODS

AA1050-H18 was used to fabricate rectangular cups. The levels chosen for the control parameters were in the operational range of AA1050-H18 aluminum alloy using deep drawing process. Each of the three control parameters was studied at three levels. The chosen control parameters are summarized in table 1.

Table 1: Control Parameters and Levels

Factor	Symbol	Level–1	Level–2	Level–3
Thickness, mm	A	1.0	1.2	1.5
Temperature, C	B	300	400	500
Coefficient of friction	C	0.10	0.15	2.00
Strain rate, 1/s	D	10	20	30

The orthogonal array (OA), L9 was selected for the present work. The parameters were assigned to the various columns of O.A. The assignment of parameters along with the OA matrix is given in table 2.

Table 2: Orthogonal Array (L9) and Control Parameters

Treat No	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

The initial dimensions of the rectangular cup without corner and edge radii are shown in figure 1. The blank size was calculated by equating the surface area of the finished drawn cup with the area of the blank. The blank dimensions are obtained by:

$$2h(l+b)+lb=l_b b_b \quad (1)$$

Where, l and l_b are the lengths the rectangular cup and the blank respectively; , band b_b are widths of the

rectangular cup and the blank respectively; h is the height of cup.

In the present the dimensions of the cup are as follows:

Cup top length, l = 60 mm

Cup top width, b = 40 mm

Height of the cup, h =75 mm.

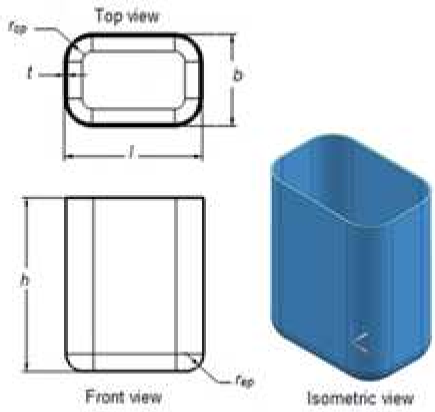

Figure 1: Initial Dimensions (with Corner & Edge Radii) of the Rectangular Cup

$$b_b = b - 2(r_{ep} + t) + 2r_c \tag{2}$$

$$l_b = l - 2(r_{ep} + t) + 2r_c$$

Where, r_{ep} is the edge radius of the punch, r_c is the blank radius and t is the thickness of the blank.

In order to avoid wrinkling in the rectangular cup, the blank must be given corner radius, r_c which can be expressed as follows:

$$r_c = \sqrt{{r_{cp}}^2 + 2r_{cp}h - 1.41r_{cp}r_{ep}} \tag{3}$$

Where, r_{cp} is the punch side corner radius.

The length and width of the punch are equal to those of the cup. The height of the punch is the height of the cup. The drawing punch must have corner radius exceeding one-tenth of the cup top length. The radius joining the bottom to the sides, r_{ep} generally ranges from three to eight times the blank thickness (t). In the present work, the corner and edge punch radii are taken as below:

$$r_{cp} = l/5 \text{ and } r_{cp} = 5t \tag{4}$$

The material flow in drawing may render some flange thickening and thinning of walls of the cup inevitable. The space for drawing is kept bigger than the sheet thickness. This space is called die clearance.

$$\text{Clearance, } c_d = t \pm \mu\sqrt{10t} \tag{5}$$

Where μ is the coefficient of friction.

The length of the die is obtained from the following equation:

$$l_d = l + 2c_d \quad (6)$$

The width of the die is obtained from the following equation:

$$b_d = b + 2c_d \quad (7)$$

The height of the die is the height of the cup.

The corner radius of the die is obtained by the addition of clearance to the punch corner radius. The edge radius of the die is eight times the blank thickness.

FINITE ELEMENT MODELING AND ANALYSIS

The finite element modeling and analysis was carried using D-FORM 3D software. The rectangular sheet blank was created with desired diameter and thickness using CAD tools (Chennakesava, 2007). The rectangular top punch, rectangular bottom hollow die were also modeled with appropriate inner and outer radius and corner radius using CAD tools. The clearance between the punch and die was calculated as in Eq. (5). The sheet blank was meshed with tetrahedral elements (Chennakesava, 2008). The modeling parameters of deep drawing process were as follows:

Number of tetrahedron elements for the blank: 21980

Number of nodes for the blank: 7460

Number of polygons for top die: 9120

Number of polygons for bottom die: 9600

The basic equations of the rigid-plastic finite element analysis are as follows:

Equilibrium equation:

$$\sigma_{ij,j} = 0 \quad (8)$$

Compatibility and incompressibility equations:

Strain rate tensor, $\dot{\varepsilon}_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i}\right)$, $\dot{\varepsilon}_{kk} = 0$ (9)

Where $u_{i,j}$ and $u_{j,i}$ are velocity vectors.

Constitutive equations:

Stress tensor, $\sigma_{ij} = \frac{2\sigma_{eq}}{3\varepsilon_{eq}}\dot{\varepsilon}_{ij}$ (10)

Where, equivalent stress, $\sigma_{eq} = \sqrt{\frac{3}{2}\left(\sigma'_{ij}, \sigma'_{ij}\right)}$ and equivalent strain, $\varepsilon_{eq} = \sqrt{\frac{3}{2}\left(\dot{\varepsilon}'_{ij}\dot{\varepsilon}'_{ij}\right)}$.

The Coulomb's friction model was given by

$$\tau_f = \mu p \quad (11)$$

Where μ is the coefficient of friction (COF), p is the normal pressure, and τ_f is the frictional shear stress.

The flow stress based on the strain hardening is computed by the following equation:

$$\sigma_f = K\varepsilon^n \tag{12}$$

Where, K and n are work hardening parameters depending on mechanical properties of material.

The flow stress equation considering the effects of the strain, strain rate and temperature is given by

$$\sigma_f = f(\varepsilon, \dot{\varepsilon}, T) \tag{13}$$

Where, ε represents the strain, $\dot{\varepsilon}$ represents the strain rate and T represents the temperature.

Johnson-Cook Model (1983) is among the most widely used mode. It connects all the deformation parameters in the following compact form.

$$\sigma_f = [\sigma + K\varepsilon^n]\left[1 + Sln\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right]\left[1 - \left(\frac{T-T_0}{T_m-T_0}\right)^m\right] \tag{14}$$

Where, $\dot{\varepsilon_0}$ is a reference strain rate taken for normalization; σ is the yield stress and K is the strain hardening factor, whereas S is a dimensionless strain rate hardening coefficient. Parameters n and m are the power exponents of the effective strain and strain rate.

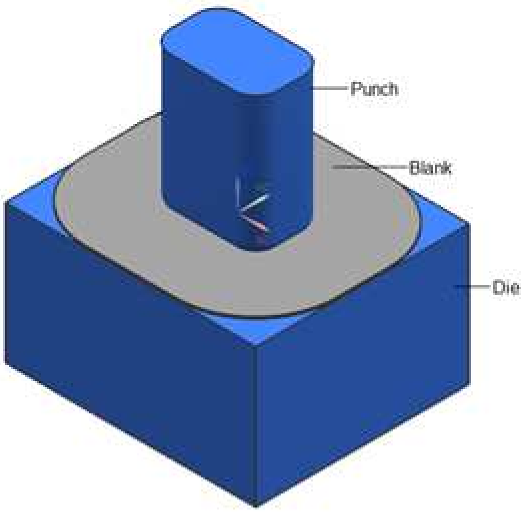

Figure 2: Blank, Punch and Die

In the present work, the contact between blank/punch and die/blank were coupled as contact pair (figure 2). The mechanical interaction between the contact surfaces was assumed to be frictional contact and modeled as Coulomb's friction model as defined in Eq. (13). The finite element analysis was chosen to find the metal flow, effective stress, height of the cup, and damage of the cup. The finite element analysis was carried out using D-FORM 3D software according to the design of experiments.

RESULTS AND DISCUSSIONS

Two trials were carried out with different meshes for each experiment. For the ANOVA (analysis of variance) the Fisher's test (F = 3.01) was carried out on all the parameters (A, B, C and D) at 90% confidence level.

Influence of Process Parameters on Effective Stress

Table 3 gives the ANOVA (analysis of variation) summary of the effective stress. The blank thickness (A) by itself

had a substantial effect (44.37%) on the effective stress. The temperature had a pronounced effect of 35.02% on the effective stress. The coefficient of friction had contributed 16.91% of the total variation observed in the effective stress. Even though the strain rate was statistically significant its contribution was negligible towards variation in the effective stress.

Table 3: ANOVA Summary of the Effective Stress

Source	Sum 1	Sum 2	Sum 3	*SS*	*V*	*V*	*F*	*P*
A	541.30	725.00	850.00	8037.03	2	4018.52	241.79	44.37
B	825.00	736.80	554.50	6343.49	2	3171.75	190.84	35.02
C	738.00	780.80	597.50	3065.06	2	1532.53	92.21	16.91
D	738.00	722.80	655.50	642.60	2	321.30	19.33	3.53
e				16.62	9	1.85	0.11	0.17
T	2842.30	2965.40	2657.50	18104.80	17			100.00

Note: *SS* Is the Sum of Square; *V* Is the Degrees of Freedom, *V* Is the Variance, *F* is the Fisher's Ratio, *P* is the Percentage of Contribution and *T* is the Sum Squares Due to Total Variation.

The effective stress had increased with an increase in the blank thickness (figure 2a). In fact, the increase in the effective stress was due to the requirement of high drawing pressures for thick sheets to undergo plastic deformation. While drawing the rectangular cups, the compressive stresses were induced along the thickness direction. These compressive stresses would increase with an increase in the blank thickness (figure 2b). The influence of temperature on the effective stress is shown in figure 3. With the increase of temperature the cup material became soft and thereby the stress induced in the cup material would decrease due to reduction of the drawing force. The influence of friction on the effective stress is shown in figure 4. In this work, the coefficient of friction was varied from 0.05 to 0.1. Therefore, the shear stress due to friction would vary from 0.05P to 0.1P, where P is the normal pressure according the Eq. (10). The normal pressures developed in the rectangular cup drawn under trials 1 and 9 are shown in figure 4b. The maximum normal pressure of 920 MPa was observed for trial 8 of the deep drawing process. The increase in the nominal contact pressure would crush the surface asperities of the blank giving rise to more real contact area. Hence, the result was the requirement of high drawing pressure to draw the rectangular cup. The stress is defined as force/area. The denominator term would increase with an increase in thickness of the blank sheet, but this increase was dominated by the required drawing force to draw the rectangular cups. Therefore, the effective was increased with the increase of friction.

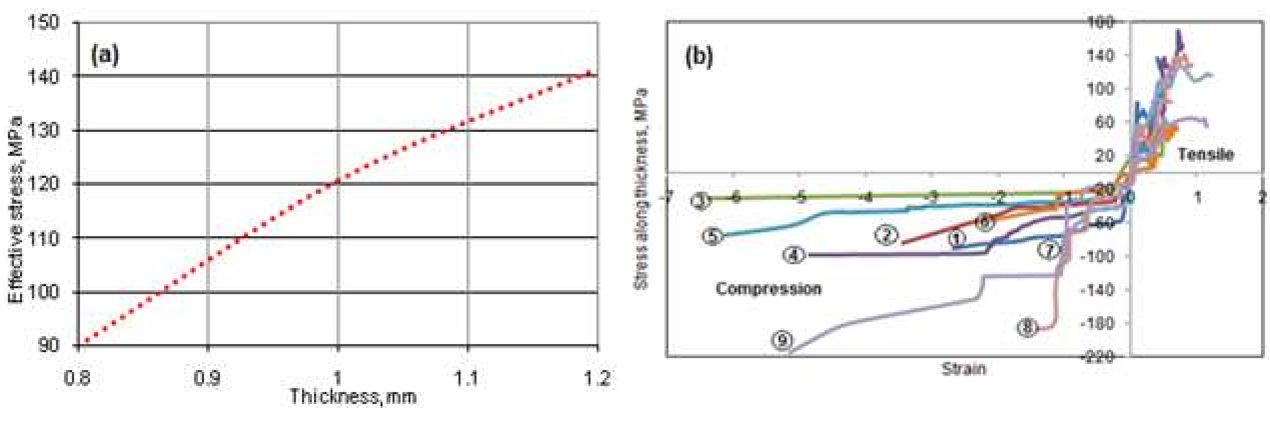

Figure 2: Influence of Blank Thickness on (A) Effective Stress and (B) Stress along Thickness Direction

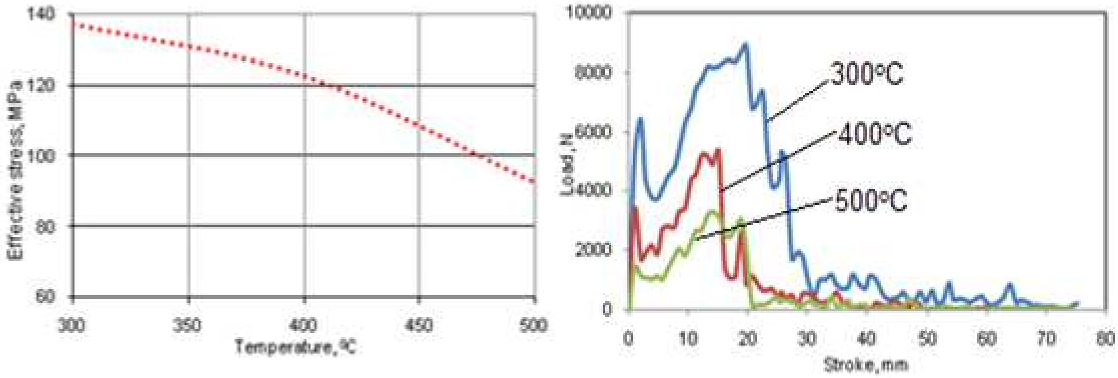

Figure 3: Influence of Temperature on (A) Effective Stress and (B) Load

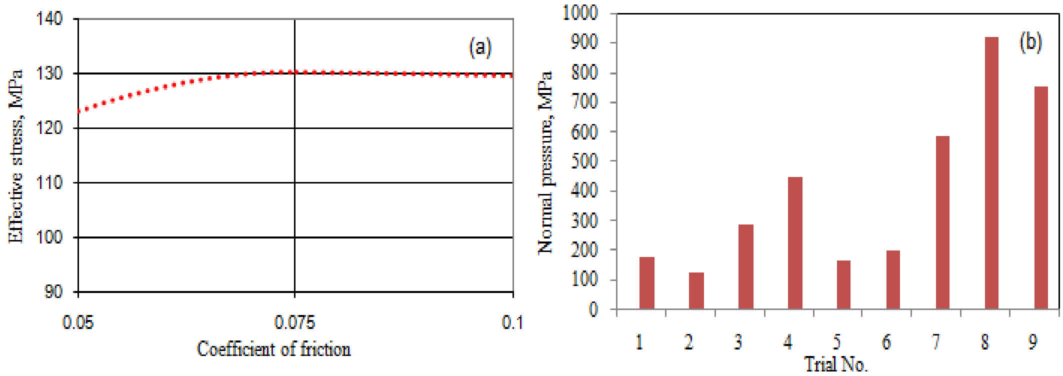

Figure 4: Influence of Friction on (A) Effective Stress and (B) Normal Pressure

The FEA results of effective stress are shown in figure 5 for various test conditions as per the design of experiments. It was found that the effective stress had exceeded the yield strength (145MPa) of the AA10550-H18 for the trails - 4 and 7. For the rest of the trials, the effective stress was lower than the yield strength.

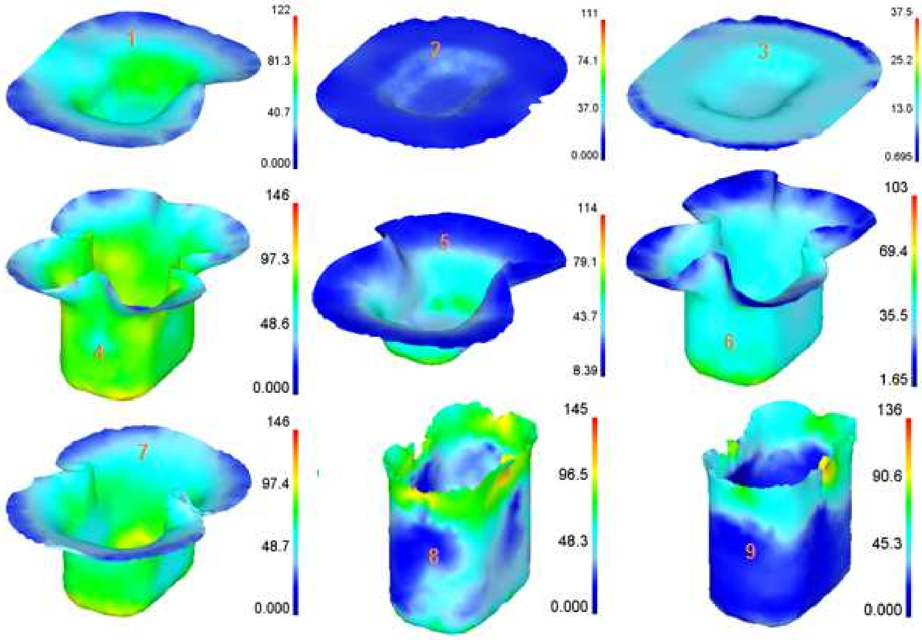

Figure 5: Effect of process parameters on the effective stress

Influence of Process Parameters on Surface Expansion Ratio

The material formability is an evaluation of how much deformation a material can undergo before failure. In the deep drawing process the plastic deformation in the surface is much more pronounced than in the thickness. The author introduces the term surface expansion ratio to measure the formability of cups

$$\text{Surface expansion ratio} = \text{Instanteneous surface area of the cup drawn}/\text{Initial blank surface area} \quad (15)$$

This depicts the formability and ductility of the blank material drawn into the cup. The ANOVA summary of surface expansion ratio is given in table 4. As per the Fisher's test (F = 3.01), the blank thickness (A) all by itself would contribute the most (76.79%) towards the variation observed in the surface expansion ratio. The contribution of the remaining all together did not exceed one-fourth of the total variation in the surface expansion ratio.

Table 4: ANOVA Summary of the Surface Expansion Ratio

Source	Sum 1	Sum 2	Sum 3	*SS*	*V*	*V*	*F*	*P*
A	8.26	10.75	16.8	6.43	2	3.22	825.64	76.79
B	10.64	12.37	12.8	0.44	2	0.22	56.41	5.25
C	13.25	12.33	10.23	0.8	2	0.4	102.56	9.55
D	13.29	10.41	12.11	0.7	2	0.35	89.74	8.36
e				0.0039	9	0	0	0.05
T	45.44	45.86	51.94	8.3739	17			100

The influence of blank thickness on the surface expansion ratio is shown in figure 6. The surface expansion ratio would increase with an increase in the blank thickness. In the forming processes, the volume of the material remains constant before and after the forming process. On account of the punch force, the blank material undergoes plastic deformation to form the cup. As the plastic deformation is irreversible, the cup retains its shape. Experimentally, it has been observed that the surface area of the cup drawn is always higher than the initial blank surface area (Reddy, 2012).

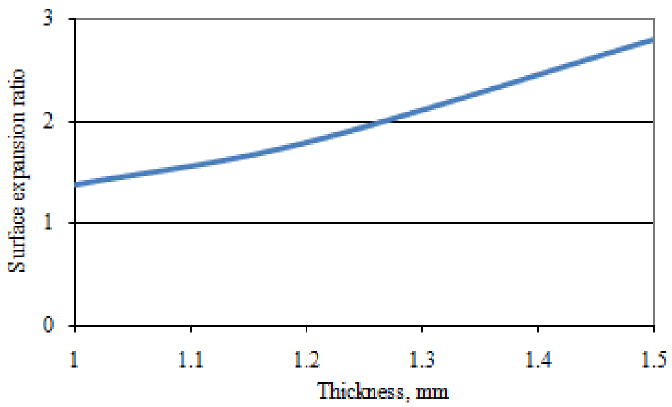

Figure 6: Influence of Blank Thickness on the Surface Expansion Ratio

The FEA results of surface expansion ratio are revealed in figure 7 for various test conditions as per the design of experiments. For the surface expansion ratio greater than 3 the height of the cups was between 55 to 75mm. For the trails-1, 2, 3, 5, 6 and 7 the surface expansion ratios were lower than 2.1 yielding the cup height in the range of 10 to 46mm. The surface expansion ratio has been found to be directly proportional to the blank thickness.

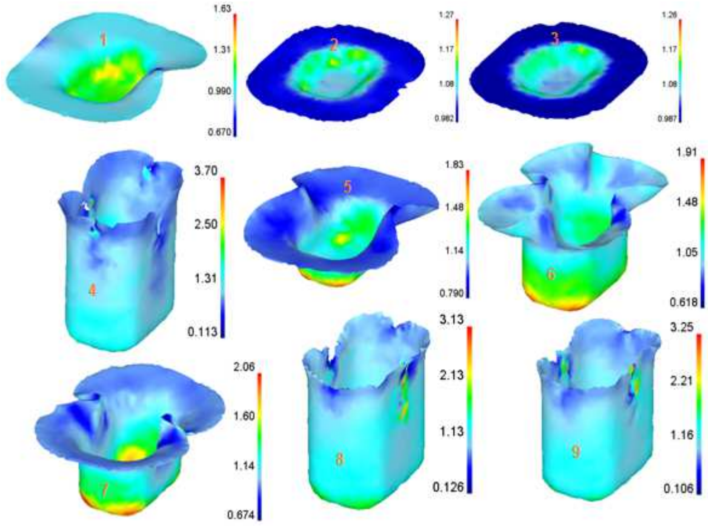

Figure 7: Effect of Process Parameters on the Surface Expansion Ratio

Influence of Process Parameters on Cup Height

As per the Fisher's test (*F* = 3.01), the blank thickness (A) all by itself would contribute the most (79.85%) towards the variation observed in the cup heights (table 5). The coefficient of friction gave 10.82% towards the total variation in the cup heights. The strain rate had a little influence on the height of the cup drawn. The influence of temperature was negligible.

Table 5: ANOVA Summary of the Effective Stress

Source	Sum 1	Sum 2	Sum 3	SS	V	V	F	P
A	85.8	279.9	377.36	7343.37	2	3671.69	2602.93	79.85
B	238.52	247.05	257.49	30.09	2	15.05	10.67	0.32
C	288.75	271.83	182.48	1086.84	2	543.42	385.24	11.82
D	265.89	194.39	282.78	733.91	2	366.96	260.14	7.98
e				1.41	9	0.16	0.11	0.03
T	878.96	993.17	1100.11	9195.62	17			100

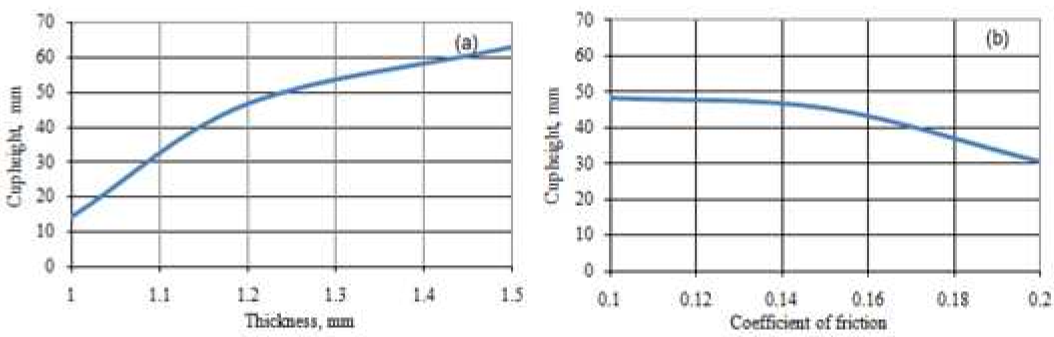

Figure 8: Influence of Blank Thickness (A) and Coefficient of Friction (B) on the Height of Cup

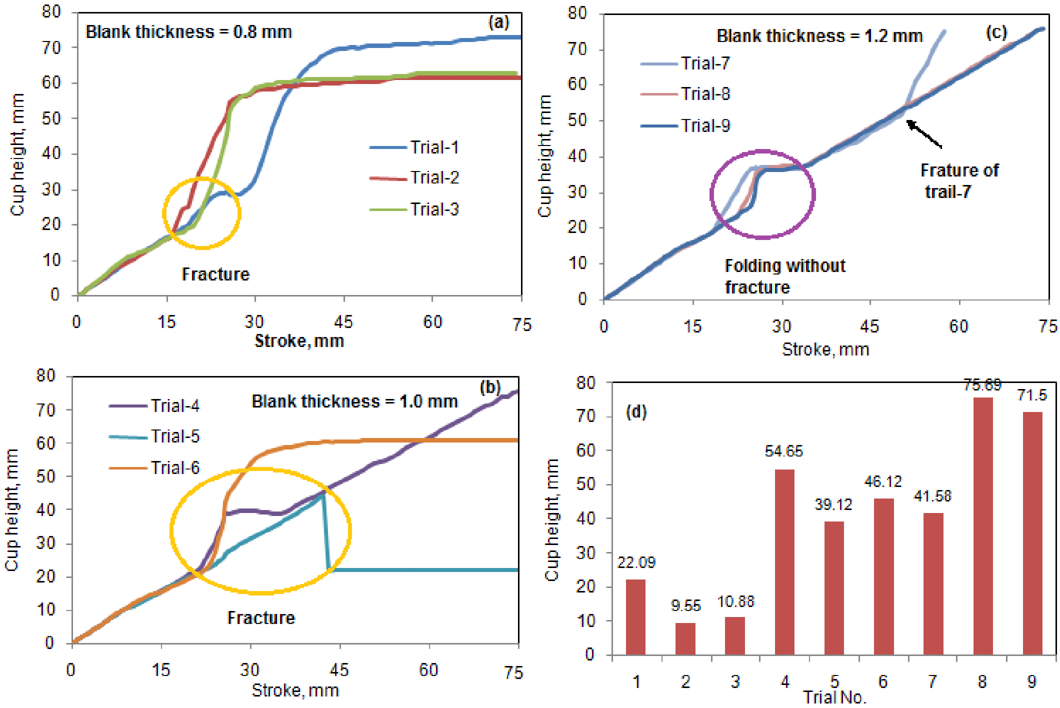

Figure 9: Displacement of Cups without BHF

The cup height would increase with an increase in the blank thickness (figure 8a). This was owing to the availability of material for the plastic deformation with the increase of blank thickness. The cup height would decrease with an increase in the coefficient of friction (figure 8b). Due to increase of the friction coefficient, the normal contact pressure between the dies and blank material would also increase. Therefore, the drawability would decrease on account of restrain by the normal pressure for free flow of metal into the die cavity. With the blank thickness of 0.8 mm, the maximum cup height drawn was 22.09 mm. The punch stroke was 15 mm for the trials 1 & 2 which could give the cup height of 10 to 11 mm. The cup height was in the range of 39 to 75 mm for the cups drawn with trials 4 to 9. The major influential characteristic of the material is the ductility. The cups which were having surface expansion ratio greater than 3.0 were drawn to the designed height (75 mm) of the rectangular cup, as shown in figure 9.

Influence of Process Parameters on Damage of Cup

The ANOVA summary of damage of cups is given in table 6. When the Fisher's test (3.01) was applied to ascertain the influence of process parameters it was found that the blank thickness (A), temperature (B), the coefficient of friction (C) and the strain rate (D), respectively had contributed 21.96%), 2.30%, 15.15% and 60.o1% of the total variation in the cups heights drawn.

Table 6: ANOVA Summary of Damage of the Cups

Source	Sum 1	Sum 2	Sum 3	*SS*	*V*	*V*	*F*	*P*
A	68.59	96.96	36.26	307.54	2	153.77	35.71	21.96
B	56.74	68.54	76.53	33.02	2	16.51	3.83	2.30
C	83.55	38.19	80.08	212.43	2	106.22	24.67	15.15
D	58.89	121.10	21.82	838.81	2	419.41	97.41	60.01
e				4.31	9	0.48	0.11	0.58
T	267.77	324.79	214.68	1396.11	17			100.00

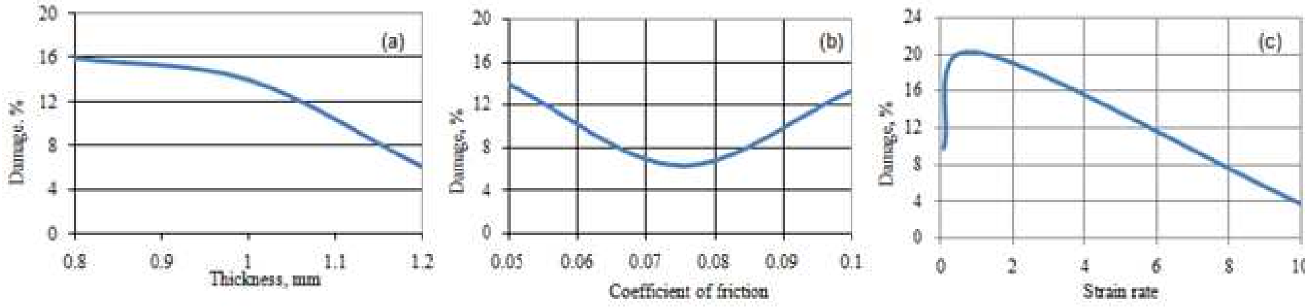

Figure 10: Influence of Blank Thickness on the Damage of Cup

The damage in the rectangular cups was decreased with an increase in the blank thickness (figure 10a). The damage was less with the friction coefficient of 0.075 (figure 10b). The damage was high with friction coefficients of 0.05 and 0.1 (figure 12). The folding of sheet was happened with the combination of low friction coefficient (0.05) and thin blank sheets (0.8 & 1.0 mm), whereas there was no or less folding with the thick blank sheets even though the friction coefficient varied from 0.05 to 0.1 (figure 11). In the case of friction between the blank and the tool, the increase of the coefficient of friction determines the wrinkling to reduce, but high values of the coefficient may cause cracks and material breakage (Hedworth & Stowell, 1971). The damage was found to be low with the strain rate of 10 1/s. (figure 10c). Haas & Shah (1971) made a research about velocity and temperature effect on flow curve of aluminum alloys. Obtained results have shown that required stress in tension necessary to obtain particular deformation is getting higher with increase of a strain rate at a constant temperature, and getting lower with increase of a temperature at a constant strain rate.

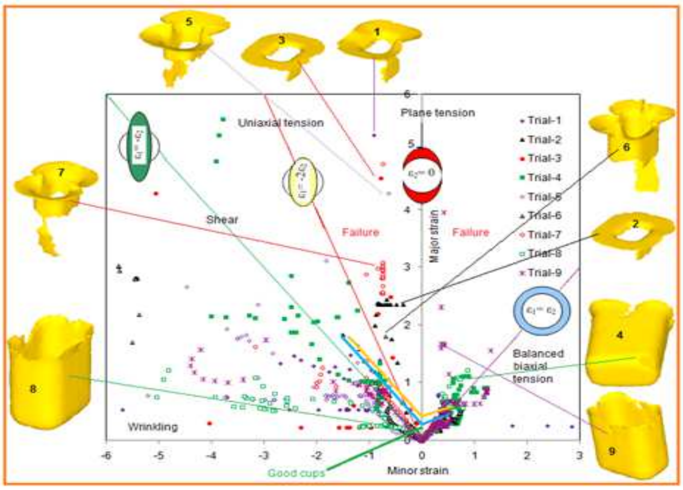

Figure 11: Forming Limit Diagram with Damage in the Cups

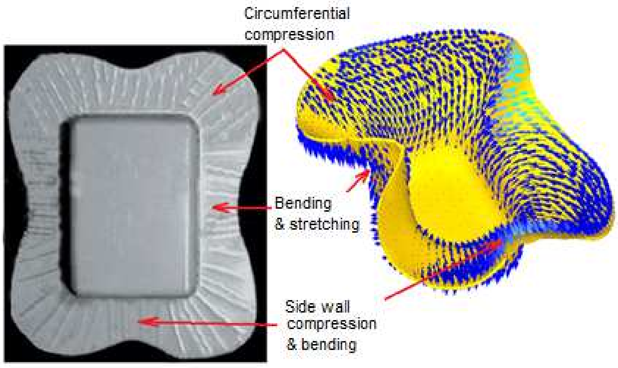

Figure 12: The Damage and Maximum Principal Strains of Cups with BHF

Figure 11 depicts the forming limit diagram with damages in the rectangular cups. The rectangular cups drawn under trials 1, 2, 3, 5, 6 and 7 were fractured on account of uniaxial tension and shear. For these cups, the minor strain was greater than the major strain in the flange area; whereas the minor strain was smaller than the major strain the wall area of the rectangular cups. The rectangular cup drawn under trial 4 was fractured due to shear and equal biaxial tension. In this rectangular the fracture was observed ate the punch corner radius. The rectangular cup drawn under trial 9 was torn in the flange area owing to equal biaxial tension. The trial 8 gave the successful rectangular cup of designed height (75 mm). On long-side walls of the cups the stretching and bending were witnessed experimentally; whereas the compression and bending were observed on short-side walls of the rectangular cups (figure 12). The circumferential compression was also noticed in the corners of the rectangular cups. Overall, the compression was higher than the tension in the blank material.

CONCLUSIONS

The blank thickness by itself has a substantial effect on the effective stress and the height of the rectangular cup drawn. With the increase of temperature the cup material has become soft and thereby the stress induced in the cup material has decreased due to reduction of the drawing force. The increase in the effective stress has been found due to the requirement of high drawing pressures for thick sheets to undergo plastic deformation. The height of the rectangular cups has found be in the range of 55 to 75mm for the surface expansion ratio greater than 3.0. The damage has turn out to be less with the friction coefficient of 0.075. From this work it is concluded that the formability of deep drawn rectangular cups is difficult with blank thickness less than 1mm.

With further research work the forming limit diagram (FLD) will be determined with applied blank holding force to material behavior at various blank thicknesses.

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